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Probe vehicle-based traffic flow estimation method without fundamental diagram

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Abstract

This paper proposes a method of estimating the traffic state based on new probe vehicle data that contain the spacing and position of probe vehicles. In this study, the probe vehicles were assumed to observe spacing by utilizing an advanced driver assistance system, which has been implemented in practice and is expected to spread in the near future. The proposed method relies on the conservation law of traffic flow but is independent of the fundamental diagram. The conservation law is utilized for reasonable aggregation of the spacing data to acquire the traffic state, namely flow, density and speed. Its independence from the fundamental diagram means that the method does not require any predetermined assumptions with regard to the traffic flow model parameters. The estimation performance was validated through a field experiment conducted under actual traffic conditions. The results confirmed that the proposed method can estimate the traffic state precisely, even if the probe vehicle penetration rate is quite low.

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Keywords: probe vehicle; traffic flow; traffic state estimation; conservation law; spacing measurement; advanced driver assistance system

1. Introduction

Probe vehicles are one of the most effective methods for collecting road traffic data because of their wide coverage area over time and space. In particular, global positioning system (GPS)-equipped probe vehicles that report their position and speed are commonly used at present (e.g., Herrera et al., 2010).

Traffic states are represented by the flow, density and speed. These variables can be estimated by using partially observed traffic data. This is known as traffic state estimation (TSE) and has been incorporated with GPS-equipped probe vehicles (e.g., Nanthawichit et al., 2003; Herrera and Bayen, 2010; Yuan et al., 2012; Mehran et al., 2012). In order to estimate the states, traffic flow models such as the LWR model (Lighthill and Whitham, 1955; Richards, 1956) and its successors have often been assumed and utilized. The LWR model is based on two assumptions: the flow–density relationship and the conservation law (CL). The flow–density relationship, which is also known as the fundamental diagram (FD), has a significant role in probe vehicle-based TSEs with regard to acquiring the flow or density from the observed speed. Most existing TSE methods assume some exogenous conditions on an FD (e.g.,

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its functional form and parameters). However, an FD is a complicated phenomenon that involves various factors (e.g., road and road user conditions) and cannot be described or predicted completely. Therefore, those exogenous assumptions for an FD may negatively affect the estimation robustness. On the other hand, the CL should always be satisfied in the estimation model unless discontinuity points such as merging/diverging sections exist. Our interest is the traffic state estimation by using probe vehicle data without FD. This requires, however, additional observed data.

Recently, several technologies for acquiring information on the surrounding environment from a running vehicle have been developed. While their original and current purposes are for advanced driver assistance systems (ADAS), such as adaptive cruise controls and autonomous driving (National Highway Traffic Safety Administration, 2013), they are also valuable for TSE because the spacing and speed of the vehicle must be measured precisely in order to enable effective ADAS. A few researchers have proposed such TSE methods by relying on simple aggregations based on the relation between density and spacing (e.g., Seo et al., 2015). One of the deficiencies of the method proposed by Seo et al. (2015) is that its precision in high resolution may not be practically well because of its independency from traffic flow dynamics. For more sophisticated and precise estimation, traffic flow models need to be explicitly considered. The problem is that almost all existing traffic flow models utilize an exogenously given FD, even though an FD can be directly observed by ADAS-equipped probe vehicles.

The objective of this study was to develop and validate a method that estimates traffic state based on the observed spacing and position data of probe vehicles. For represent dynamics of traffic, the method utilizes a CL. On the other hand, it does not use any predetermined FD in order to exploit the advantages of spacing measurement technology. The developed method was verified with using actual data taken from a field experiment performed on an urban expressway. Section 2 describes the development of the method. Section 3 and 4 describes the validation of the proposed method.

2. Estimation method

This section describes the method of estimating the traffic state based on the observed spacing and position data from probe vehicles.

2.1. Concepts

The method estimates traffic states in a road section where some of the vehicles in the flow are probes that measure the geographic position and spacing of the vehicle ahead without any errors. The road section's schematics are assumed to be known to analysts. The probe vehicles' driving behavior is assumed to be the same as that of non-probe vehicles, i.e., the probes are randomly sampled from all of the vehicles. In addition, the traffic flow is assumed to be single-lane traffic that satisfies the first-in first-out (FIFO) condition in order to simplify the situation.

The spacing observed by a vehicle at a time point depends on microscopic vehicular phenomena that depend on macroscopic traffic flow phenomena. For example, spacing of a vehicle takes volatile value which is mainly determined by whether the vehicle was the leader of a platoon or not; meanwhile, development of the platoons is determined by the global traffic state. Therefore, aggregation is needed in order to estimate the traffic state from the observed vehicular variables. In this method, the observed vehicular variables are aggregated based on the CL. Specifically, the number of vehicles between two specific probe vehicles is a constant along a section where flow discontinuity points (e.g., a node in a road network) do not exist. This number of vehicles is to be estimated by aggregating data observed by the two boundary probe vehicles. The estimation procedure is as follows:

Step 1 The number of vehicles between two consecutive probe vehicles and two consecutive discontinuity points is estimated based on the observed data of the two probe vehicles.

Step 2 The cumulative count at the probe vehicle trajectories is calculated from the estimated number of vehicles.

Step 3 The continuous cumulative count over the entire time–space is estimated by interpolating one at the probe vehicle trajectories.

Step 4 The traffic state (i.e., flow, density and speed) is derived by partially differentiating the continuous cumulative count.